

# Planck 2013 results. XXIX. The Planck catalogue of Sunyaev–Zeldovich sources: Addendum

Planck Collaboration: P. A. R. Ade<sup>99</sup>, N. Aghanim<sup>68\*</sup>, C. Armitage-Caplan<sup>104</sup>, M. Arnaud<sup>81</sup>, M. Ashdown<sup>78,7</sup>, F. Atrio-Barandela<sup>21</sup>, J. Aumont<sup>68</sup>, H. Aussel<sup>81</sup>, C. Baccigalupi<sup>97</sup>, A. J. Banday<sup>110,11</sup>, R. B. Barreiro<sup>75</sup>, R. Barrena<sup>74</sup>, M. Bartelmann<sup>108,87</sup>, J. G. Bartlett<sup>1,76</sup>, E. Battaner<sup>113</sup>, K. Benabed<sup>69,107</sup>, A. Benoît<sup>66</sup>, A. Benoit-Lévy<sup>29,69,107</sup>, J.-P. Bernard<sup>110,11</sup>, M. Bersanelli<sup>41,58</sup>, P. Bielewicz<sup>110,11,97</sup>, I. Bikmaev<sup>24,3</sup>, J. Bobin<sup>81</sup>, J. J. Bock<sup>76,12</sup>, H. Böhringer<sup>88</sup>, A. Bonaldi<sup>77</sup>, J. R. Bond<sup>10</sup>, J. Borrill<sup>16,101</sup>, F. R. Bouchet<sup>69,107</sup>, M. Bridges<sup>78,7,72</sup>, M. Bucher<sup>1</sup>, R. Burenin<sup>100,91</sup>, C. Burigana<sup>57,39</sup>, R. C. Butler<sup>57</sup>, J.-F. Cardoso<sup>82,1,69</sup>, P. Carvalho<sup>7</sup>, A. Catalano<sup>83,80</sup>, A. Challinor<sup>72,78,13</sup>, A. Chamballu<sup>81,18,68</sup>, R.-R. Chary<sup>65</sup>, X. Chen<sup>65</sup>, H. C. Chiang<sup>33,8</sup>, L.-Y. Chiang<sup>71</sup>, G. Chon<sup>88</sup>, P. R. Christensen<sup>93,44</sup>, E. Churazov<sup>87,100</sup>, S. Church<sup>103</sup>, D. L. Clements<sup>64</sup>, S. Colombi<sup>69,107</sup>, L. P. L. Colombo<sup>28,76</sup>, B. Comis<sup>83</sup>, F. Couchot<sup>79</sup>, A. Coulais<sup>80</sup>, B. P. Crill<sup>76,94</sup>, A. Curto<sup>7,75</sup>, F. Cuttaia<sup>57</sup>, A. Da Silva<sup>14</sup>, H. Dahle<sup>73</sup>, L. Danese<sup>97</sup>, R. D. Davies<sup>77</sup>, R. J. Davis<sup>77</sup>, P. de Bernardis<sup>40</sup>, A. de Rosa<sup>57</sup>, G. de Zotti<sup>53,97</sup>, J. Delabrouille<sup>1</sup>, J.-M. Delouis<sup>69,107</sup>, J. Démoclès<sup>81</sup>, F.-X. Désert<sup>61</sup>, C. Dickinson<sup>77</sup>, J. M. Diego<sup>75</sup>, K. 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Murphy<sup>92</sup>, P. Naselsky<sup>93,44</sup>, A. Nastasi<sup>68</sup>, F. Nati<sup>40</sup>, P. Natoli<sup>39,5,57</sup>, N. P. H. Nesvadba<sup>68</sup>, C. B. Netterfield<sup>23</sup>, H. U. Nørgaard-Nielsen<sup>19</sup>, F. Noviello<sup>77</sup>, D. Novikov<sup>64</sup>, I. Novikov<sup>93</sup>, I. J. O’Dwyer<sup>76</sup>, M. Olamaie<sup>7</sup>, S. Osborne<sup>103</sup>, C. A. Oxborrow<sup>19</sup>, F. Paci<sup>97</sup>, L. Pagano<sup>40,60</sup>, F. Pajot<sup>68</sup>, D. Paoletti<sup>57,59</sup>, F. Pasian<sup>55</sup>, G. Patanchon<sup>1</sup>, T. J. Pearson<sup>12,65</sup>, O. Perdereau<sup>79</sup>, L. Perotto<sup>83</sup>, Y. C. Perrot<sup>7</sup>, F. Perrotta<sup>97</sup>, F. Piacentini<sup>40</sup>, M. Piat<sup>1</sup>, E. Pierpaoli<sup>28</sup>, D. Pietrobon<sup>76</sup>, S. Plaszczynski<sup>79</sup>, E. Pointecouteau<sup>110,11</sup>, G. Polenta<sup>5,54</sup>, N. Ponthieu<sup>68,61</sup>, L. Popa<sup>70</sup>, T. Poutanen<sup>51,32,2</sup>, G. W. Pratt<sup>81</sup>, G. Prézeau<sup>12,76</sup>, S. Prunet<sup>69,107</sup>, J.-L. Puget<sup>68</sup>, J. P. Rachen<sup>25,87</sup>, W. T. Reach<sup>111</sup>, R. Rebolo<sup>74,17,45</sup>, M. Reinecke<sup>87</sup>, M. Remazeilles<sup>77,68,1</sup>, C. Renault<sup>83</sup>, S. Ricciardi<sup>57</sup>, T. Riller<sup>87</sup>, I. Ristorcelli<sup>110,11</sup>, G. Rocha<sup>76,12</sup>, C. Rosset<sup>1</sup>, G. Roudier<sup>1,80,76</sup>, M. Rowan-Robinson<sup>64</sup>, J. A. Rubiño-Martín<sup>74,45</sup>, C. Rumsey<sup>7</sup>, B. Rusholme<sup>65</sup>, M. Sandri<sup>57</sup>, D. Santos<sup>83</sup>, R. D. E. Saunders<sup>7,78</sup>, G. Savini<sup>95</sup>, M. P. Schammel<sup>7</sup>, D. Scott<sup>27</sup>, M. D. Seiffert<sup>76,12</sup>, E. P. S. Shellard<sup>13</sup>, T. W. Shimwell<sup>7</sup>, L. D. Spencer<sup>99</sup>, J.-L. Starck<sup>81</sup>, V. Stolyarov<sup>7,78,102</sup>, R. Stompor<sup>1</sup>, A. Streblyanska<sup>74,45</sup>, R. Sudiwala<sup>99</sup>, R. Sunyaev<sup>87,100</sup>, F. Sureau<sup>81</sup>, D. Sutton<sup>72,78</sup>, A.-S. Suur-Uski<sup>32,51</sup>, J.-F. Sygnet<sup>69</sup>, J. A. Tauber<sup>48</sup>, D. Tavagnacco<sup>55,42</sup>, L. Terenzi<sup>57</sup>, L. Toffolatti<sup>22,75</sup>, M. Tomasi<sup>58</sup>, D. Tramonte<sup>74,45</sup>, M. Tristram<sup>79</sup>, M. Tucci<sup>20,79</sup>, J. Tuovinen<sup>90</sup>, M. Türler<sup>62</sup>, G. Umata<sup>52</sup>, L. Valenziano<sup>57</sup>, J. Valiviita<sup>51,32,73</sup>, B. Van Tent<sup>84</sup>, L. Vibert<sup>68</sup>, P. Vielva<sup>75</sup>, F. Villa<sup>57</sup>, N. Vittorio<sup>43</sup>, L. A. Wade<sup>76</sup>, B. D. Wandelt<sup>69,107,37</sup>, M. White<sup>34</sup>, S. D. M. White<sup>87</sup>, D. Yvon<sup>18</sup>, A. Zacchei<sup>55</sup>, and A. Zonca<sup>36</sup>

(Affiliations can be found after the references)

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## ABSTRACT

We update the all-sky *Planck* catalogue of 1227 clusters and cluster candidates (PSZ1) published in March 2013, derived from Sunyaev–Zeldovich (SZ) effect detections using the first 15.5 months of *Planck* satellite observations. *addendum*, we deliver an updated version of the PSZ1 catalogue, reporting the further confirmation of 86 *Planck*-discovered clusters. In total, the PSZ1 now contains 947 confirmed clusters, of which 214 were confirmed as newly discovered clusters through follow-up observations undertaken by the *Planck* Collaboration. The updated PSZ1 contains redshifts for 913 systems, of which 736 (~ 80.6%) are spectroscopic, and associated mass estimates derived from the  $Y_z$  mass proxy. We also provide a new SZ quality flag, derived from a novel artificial neural network classification of the SZ signal, for the remaining 280 candidates. Based on this assessment, the purity of the updated PSZ1 catalogue is estimated to be 94%. In this release, we provide the full updated catalogue and an additional readme file with further information on the *Planck* SZ detections.

**Key words.** large-scale structure of Universe – Galaxies: clusters: general – Catalogs

## 1. Introduction

\* Corresponding author: N. Aghanim  
u-psud.fr

nabila.aghanim@ias.

It is only recently that cluster samples selected via their Sunyaev–Zeldovich (SZ) signal have reached a significant sizes,

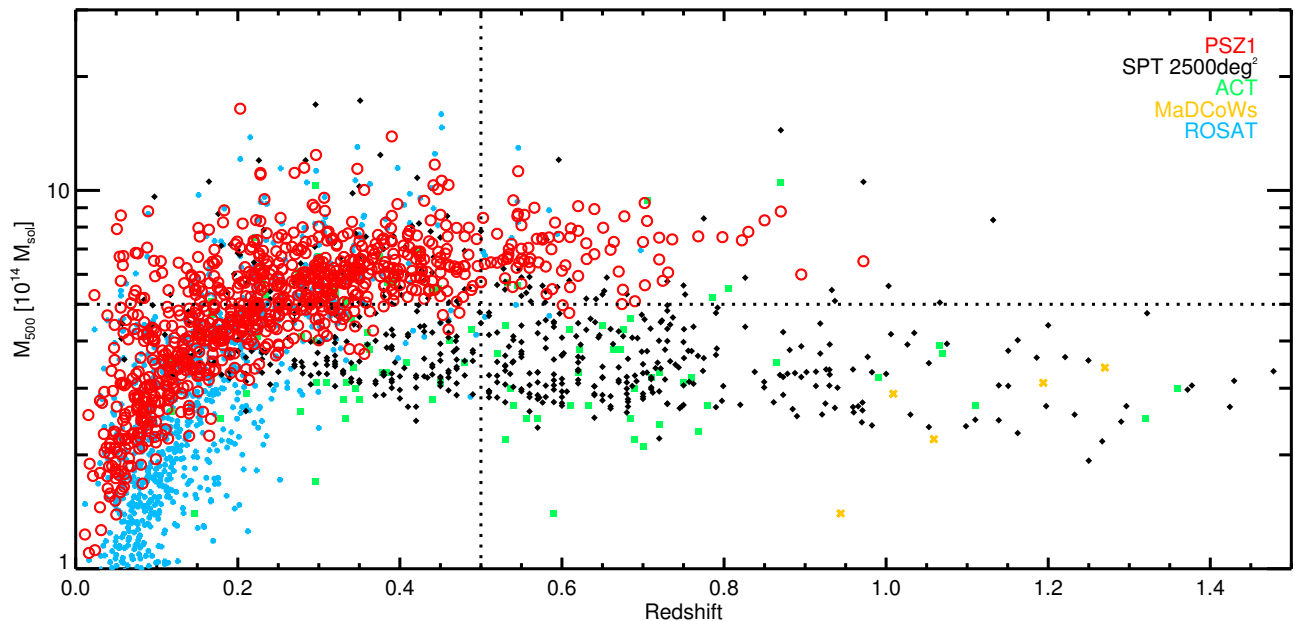


Fig. 1: Distribution in the  $M$ – $z$  plane of the *Planck* SZ cluster catalogue (open red circles) (Planck Collaboration XXIX 2013) compared with those from SPT (black) (Reichardt et al. 2013; Bleem et al. 2014) and ACT (green) (Marriage et al. 2011; Hasselfield et al. 2013), MaDCoWs (yellow) (Brodwin et al. 2014), and NORAS and REFLEX from the MCXC meta-catalogue (blue) (Piffaretti et al. (2011) and references therein). Some clusters may appear several times as distinct points due to differences in the mass estimate between surveys. The black dotted lines show the *Planck* mass limit for the medium-deep survey zone at 20% completeness for a redshift limit of  $z = 0.5$ .

e.g., the Early SZ (ESZ) catalogue from the *Planck* Satellite<sup>1</sup> (Planck Collaboration VIII 2011; Planck Collaboration XXIX 2013), and catalogues from the South Pole Telescope (SPT, Reichardt et al. 2013; Bleem et al. 2014) and the Atacama Cosmology Telescope (ACT, Marriage et al. 2011; Hasselfield et al. 2013). These are now considered as new reference samples for cluster studies and associated cosmological analyses.

The present note describes updates to the construction and properties of the *Planck* catalogue of SZ sources PSZ1, (hereafter PXXIX2013, Planck Collaboration XXIX 2013), released in March 2013 as part of the first *Planck* data delivery. The PSZ1 catalogue contains 1227 entries, including 683 so-called *previously-known* clusters. This category corresponds to the association of *Planck* SZ source detections with known clusters from the literature. The association is set to the first identifier as defined in the hierarchy adopted by PXXIX2013, namely: (i) identification with MCXC clusters (Piffaretti et al. 2011); (ii) identification with Abell and Zwicky objects; (iii) identification with clusters derived from SDSS-based catalogues (primarily from Wen et al. (2012)); (iv) identification with clusters from SZ catalogues (Hasselfield et al. 2013; Reichardt et al. 2013); (v) searches in the NED and SIMBAD databases. Considerable added value, including consolidated redshift and mass estimates (Fig. 1), has been obtained through compilation of this ancillary information.

<sup>1</sup> *Planck* (<http://www.esa.int/Planck>) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states (in particular the lead countries France and Italy), with contributions from NASA (USA) and telescope reflectors provided by a collaboration between ESA and a scientific consortium led and funded by Denmark.

Since its delivery March 2013, we have continued to update the PSZ1 catalogue by focusing on the confirmation of newly-discovered clusters in PSZ1. This process has first involved updating the redshifts of some previously-known clusters (Sect. 2). We have also made use of recent results from dedicated follow-up observations conducted by the *Planck* Collaboration with the RTT150 (Planck Collaboration et al. 2014) and ENO telescopes (Planck Collaboration 2015, in prep.), which together have allowed us to observe and measure redshifts for  $\sim 150$  PSZ1 sources (Sect. 3.1). We have also used published results from PanSTARRS (Liu et al. 2014) and from the latest SPT catalogue (Bleem et al. 2014), as described in Sects. 3.3 and 3.5. For all clusters with measured redshifts, we have computed the estimated masses using the  $Y_z$  mass proxy (Arnaud et al. 2014 and PXXIX2013; Sec. 4). Finally, we have revisited the cluster candidate classification scheme, which in PXXIX2013 was organised into three classes (*class-1, 2, 3*) in order of decreasing reliability. As described in Sect. 5, we have now used the SZ spectral energy distribution (SED) to refine the quality assessment of the cluster candidates by adopting a new, novel quality flag derived from the Artificial Neural Network analysis developed by Aghanim et al. (2014).

## 2. Redshift updates for *previously-known* clusters

In the external validation process performed in PXXIX2013, a total of 683 PSZ1 sources were associated with clusters published in X-ray, optical, or SZ catalogues, or with clusters found in the NED or SIMBAD databases. We refer to these as *previously-known clusters*. Their redshifts, when available, were compiled from the literature and a consolidated value was provided with the PSZ1 catalogue. In the present update, we first re-examine the *previously-known* clusters of the PSZ1 catalogue.

The dedicated follow-up of *Planck* PSZ1 clusters with RTT150 described in [Planck Collaboration et al. \(2014\)](#) provided updates to the redshifts of 19 *previously-known* clusters. The follow-up of *Planck* PSZ1 clusters with ENO telescopes further updated the redshifts of five *previously-known* clusters.

We have updated the redshifts of ten PSZ1 sources associated with SPT clusters provided in [Bleem et al. \(2014\)](#). Finally, we have queried the NED and SIMBAD databases, and searched in the cluster catalogues constructed from the SDSS data (namely [Wen et al. 2012](#) and [Roza et al. 2014](#)), for additional spectroscopic redshifts. When these were available, we report them in the updated version of the PSZ1 catalogue. The full process led us to change the redshifts of 34 *previously-known* PSZ1 clusters. We have also changed the published photometric redshift estimate of one ACT cluster (ACT-CL J0559-5249) to a spectroscopic redshift value.

In summary, 69 sources from the PSZ1 catalogue associated with *previously-known* clusters now have updated redshifts. Most of these consist of updates from photometric to spectroscopic values; however, eight redshifts were measured for the first time for *previously-known* clusters.

### 3. *Planck*-discovered clusters

The PSZ1 catalogue contained 366 cluster candidates, classified as *class-1* to 3 in order of decreasing reliability, and 178 *Planck*-discovered clusters confirmed mostly with dedicated follow-up programmes undertaken by the *Planck* Collaboration. Since the delivery of the PSZ1 catalogue in March 2013, a number of additional confirmations, including results from the community, were performed and redshifts were updated from photometric estimates to spectroscopic values.

Combining the results from follow-up with the RTT150 [Planck Collaboration et al. \(2014\)](#), ENO telescopes ([Planck collaboration 2015, in prep.](#)), [Liu et al. \(2014\)](#), [Roza et al. \(2014\)](#), and [Bleem et al. \(2014\)](#), a total of 86 PSZ1 sources have been newly confirmed as *Planck*-discovered clusters with measured redshifts.

#### 3.1. From RTT150 results

As part of the *Planck* Collaboration optical follow-up programme, candidates were observed with the Russian Turkish Telescope (RTT150<sup>2</sup>, [Planck Collaboration et al. 2014](#)) within the Russian quota of observational time, provided by Kazan Federal University and Space Research Institute (IKI, Moscow). Direct images and spectroscopic redshift measurements were obtained using TÜBİTAK Faint Object Spectrograph and Camera (TFOSC<sup>3</sup>). For the highest-redshift clusters, complementary spectroscopic observations were performed with the BTA 6-m telescope of the SAO RAS using the SCORPIO focal reducer and spectrometer ([Afanasiev & Moiseev 2005](#)).

These observations have confirmed and measured redshifts for a total of 24 new candidates. Eleven of these have spectroscopic redshifts. We have updated the PSZ1 catalogue by including these newly-measured redshifts.

<sup>2</sup> <http://hea.iki.rssi.ru/rtt150/en/index.php>.

<sup>3</sup> <http://hea.iki.rssi.ru/rtt150/en/index.php?page=tfosc>.

#### 3.2. From ENO telescopes

Also as part of the *Planck* Collaboration optical follow-up programme, candidates were observed at European Northern Observatory (ENO<sup>4</sup>) telescopes, both in imaging (at IAC80, INT and WHT) and spectroscopy (at NOT, GTC, INT and TNG). The observations were obtained as part of proposals for the Spanish CAT time, and an *International Time Programme (ITP)*, accepted by the International Scientific Committee of the Roque de los Muchachos and Teide observatories. We summarise here the main results of these observing programmes. Further details will be presented in a companion article (*Planck* Collaboration 2015, in prep.).

These observations have confirmed and provided new redshifts for a total of 26 candidates, that are reported in the updated PSZ1 catalogue. These include the confirmation of 12 SZ sources as newly-discovered clusters: two *class-1*, high reliability candidates, five *class-2*, and five *class-3* candidates.

#### 3.3. From PanSTARRS

Based on the Panoramic Survey Telescope & Rapid Response System (PanSTARRS, [Kaiser et al. 2002](#)) data, [Liu et al. \(2014\)](#) have searched for optical confirmation of the 237 *Planck* SZ detections that overlap the PanSTARRS footprint.

We only report here the redshifts for unambiguously confirmed clusters. Of these, 15 objects were included in the RTT150 follow-up, for which the redshifts are published in [Planck Collaboration et al. \(2014\)](#), and three objects were included in the ESO follow-up described above. In these cases, we report the *Planck* Collaboration follow-up redshift values in the updated PSZ1 catalogue. An additional two *Planck* clusters confirmed by PanSTARRS have a counterpart in the [Roza et al. \(2014\)](#) catalogue, with spectroscopic redshifts that we update in the PSZ1 catalogue.

A total of 40 *Planck*-discovered clusters are confirmed, for the first time, by [Liu et al. \(2014\)](#) in the PanSTARRS survey. All of these have measured photometric redshifts that we have reported in the updated PSZ1 catalogue.

#### 3.4. From SPT

A new catalogue of SZ clusters detected with the South Pole Telescope (SPT) cluster catalogue was published in [Bleem et al. \(2014\)](#). It provides an ensemble of spectroscopic and photometric redshifts. Four candidate *class-1* and 2 clusters from the PSZ1 catalogue were confirmed and have photometric redshifts in [Bleem et al. \(2014\)](#). These are included in the updated PSZ1 catalogue.

#### 3.5. From SDSS-RedMapper catalogue

Comparison with the SDSS-based catalogue from [Roza et al. \(2014\)](#) provided confirmation and new redshift values for five *Planck*-discovered clusters. This includes confirmation of two *Planck* cluster candidates (one *class-2* and one *class-3* candidate). We use the spectroscopic redshift values available in the [Roza et al. \(2014\)](#) in the updated PSZ1 catalogue.

<sup>4</sup> ENO: <http://www.iac.es/eno.php?lang=en>.

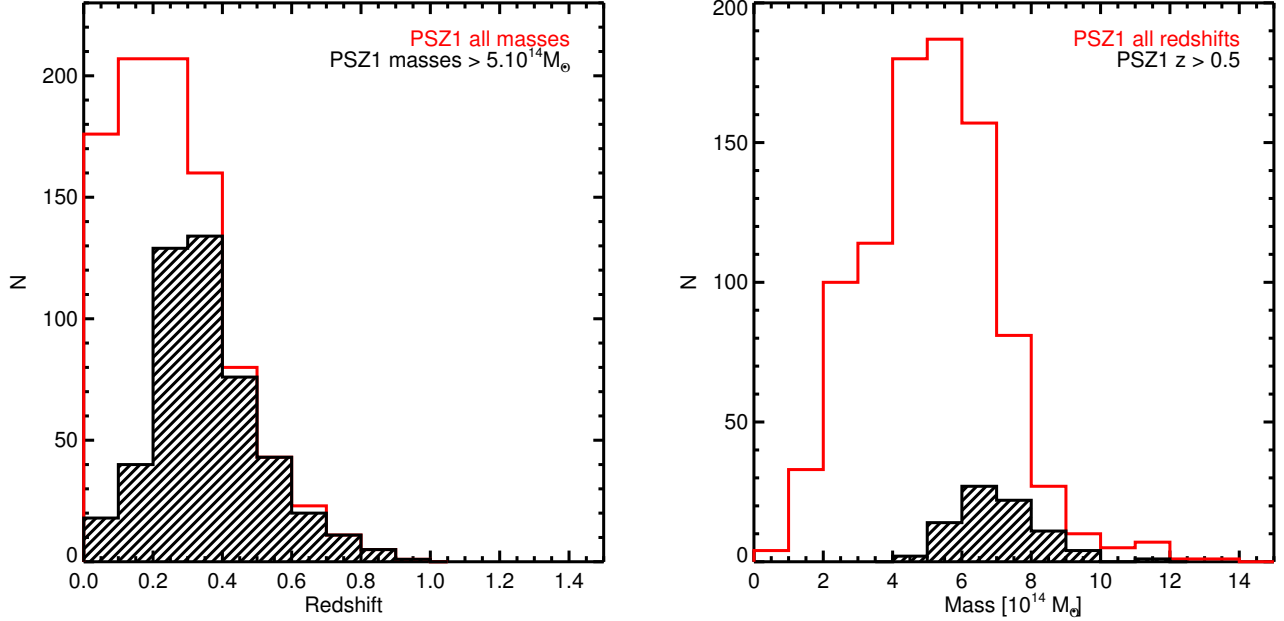


Fig. 2: Distribution of redshifts (left panel) and masses (right panel) for the *Planck* SZ clusters. The black shaded area represents the population of clusters above redshift of 0.5 (in the right panel) and having a mass above  $5 \times 10^{14} M_{\odot}$  (in the left panel).

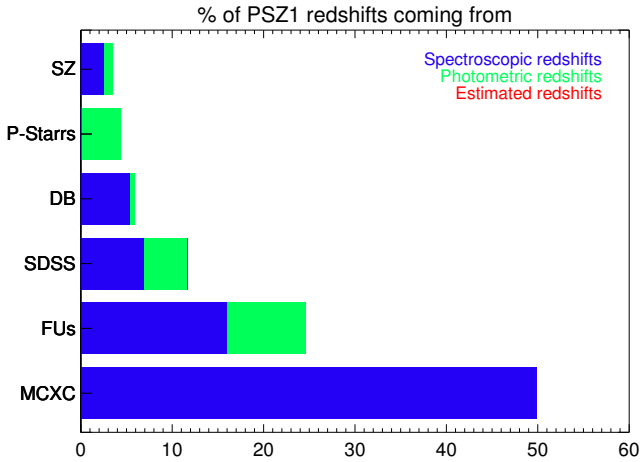


Fig. 3: Percentage of origin and type (photometric, spectroscopic) of the redshifts reported in PSZ1. To date associations with MCXC clusters provide 49.8% of the redshifts, all spectroscopic. Follow up observations by the *Planck* collaboration (FUs) provide 24.6% of the redshifts, of which 64.73% are spectroscopic. Associations with clusters from SDSS-based catalogues result in 11.7% of all redshifts, of which 58.9% are spectroscopic. Redshifts from the NED and SIMBAD databases represent 5.9% of all redshifts, with 90.7% of them spectroscopic. The confirmation from PanSTARRS data provides 4.4% of the total number of redshifts, all of them photometric. Finally the association with SZ catalogues (SPT and ACT) represents 3.5% of all redshifts, of which 71.9% are spectroscopic.

#### 4. Mass estimate

The size–flux degeneracy discussed in, e.g., [Planck Collaboration VIII \(2011\)](#) and PXXIX2013 can be broken

when  $z$  is known, using the  $M_{500}-D_A^2 Y_{500}$  relation between  $\theta_{500}$  and  $Y_{500}$  see ([Arnaud et al. 2014](#)). The  $Y_{500}$  parameter, denoted  $Y_z$ , is derived from the intersection of the  $M_{500}-D_A^2 Y_{500}$  relation and the size–flux degeneracy curve. It is the SZ mass proxy  $Y_z$  that is equivalent to the X-ray mass proxy  $Y_X$ .

For all the *Planck* clusters with measured redshifts,  $Y_z$  was computed for our assumed cosmology, allowing us to derive an homogeneously-defined SZ mass proxy, denoted  $M_{500}^{Y_z}$ , based on X-ray calibration of the scaling relations (see discussion in PXXIX2013). We show in Fig. 2 (right panel, in red) the distribution of masses obtained from the SZ-based mass proxy for all clusters with measured redshift. Note that since we use an X-ray calibration of the scaling relations, these masses are uncorrected for any bias due to the assumption of hydrostatic equilibrium in the X-ray mass analysis. The shaded black area shows the distribution of masses for clusters with redshifts higher than 0.5. They represent a total of 78 clusters.

#### 5. Cluster candidates

Since the delivery of the *Planck* catalogue and the confirmation in this *addendum* of 86 candidates as new clusters, the updated PSZ1 catalogue now contains 280 cluster candidates. In the original PSZ1, these latter were classified as *class-1* to 3 in order of decreasing reliability; the reliability being defined empirically from the combination of internal *Planck* quality assessment and ancillary information (e.g., searches in RASS, WISE, SDSS data). The updated PSZ1 catalogue contains 24 high quality (*class-1*) SZ detections whereas lower reliability *class-2* and 3 candidates represent 130 and 126 SZ sources, respectively.

With the updated PSZ1 catalogue, we now provide a new objective quality assessment of the SZ sources derived from an artificial neural-network analysis. The construction, training and validation of the network is based on the analysis of the Spectral Energy Distribution (SED) of the SZ signal in the *Planck* chan-

nels. The implementation is discussed in detail by Aghanim et al. (2014). The neural network was trained with an ensemble of three samples: the confirmed clusters in the PSZ1 catalogue representing good/high-quality SZ signal; the *Planck* Catalogue of Compact Sources source, representing the IR and radio-source induced detections; and random positions on the sky as examples of noise-induced, very low reliability, detections.

In practice, we provide for each SZ source of the updated PSZ1 catalogue a neural-network quality flag,  $Q_N$ , defined as in Aghanim et al. (2014). This flag separates the high quality SZ detections from the low quality sources such that  $Q_N < 0.4$  identifies low-reliability SZ sources with a high degree of success. Figure 4 summarises for each class of *Planck* cluster candidate the number of sources below and above the threshold value of  $Q_N = 0.4$ . The *class-1* cluster candidates all have  $Q_N > 0.4$  except for one source for which  $Q_N = 0.39$ . The fraction of ‘good’  $Q_N > 0.4$  SZ detections in the *class-2* category is about 80%, while the fraction of  $Q_N > 0.4$  candidates drops to about 30% for the *class-3* cluster-candidates.

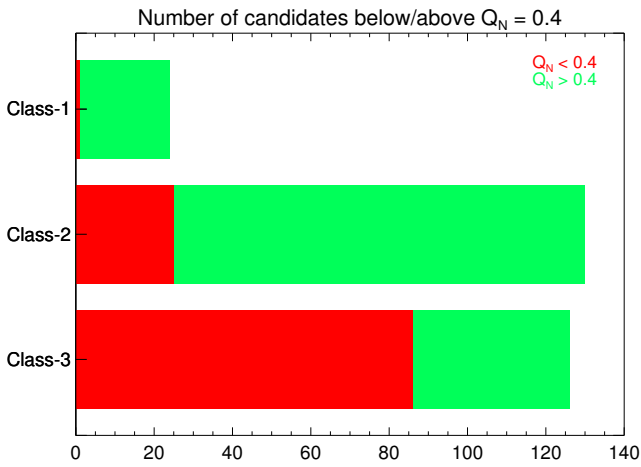


Fig. 4: Number of *Planck* cluster-candidates below and above the neural-network quality flag threshold  $Q_N = 0.4$ , denoting a high-quality SZ detection, for each reliability class.

## 6. Summary

We have updated the *Planck* catalogue of SZ-selected sources detected in the first 15.5 months of observations. The catalogue contains 1227 detections and was validated using external X-ray and optical/NIR data, alongside a multi-frequency follow-up programme for confirmation.

The updated PSZ1 catalogue now contains 947 confirmed clusters, including 264 brand-new clusters, of which 214 have been confirmed by the *Planck* Collaboration’s follow-up programme. The remaining 280 cluster candidates have been divided into three classes according to their reliability, i.e., the quality of evidence that they are likely to be *bona fide* clusters. To date, high quality SZ detections in PSZ1 represent 24 sources, all of which are classified as high-quality by our neural-network quality assessment procedure. Lower reliability, *class-2* and *class-3* candidates represent 130 and 126 SZ sources respectively (Table 1). We find that  $\sim 80\%$  of the *class-2* candidates are classified as high-quality by our neural-network quality assessment

procedure, whereas only 35% of the *class-3* sources are considered as high-quality SZ detections. Based on this assessment, the purity of the updated PSZ1 catalogue is  $\sim 94\%$ .

A total of 913 *Planck* clusters (i.e., 74.2% of all SZ detections) now have measured redshifts, of which 736 are spectroscopic values (i.e., 80.6% of all redshifts). The left-hand panel of Fig. 2 shows the distribution in redshift of all clusters (red), and for the clusters with masses above  $5 \times 10^{14} M_\odot$  (shaded black). The median redshift of the PSZ1 catalogue is about 0.23, and of order 35% of the *Planck* clusters lie at redshifts above  $z = 0.3$ .

The origins and types of redshifts are shown in Fig. 3. Association with MCXC clusters (Piffaretti et al. 2011) provides about 49.8% of the redshifts, all of which are spectroscopic. Follow up observations undertaken by the *Planck* Collaboration provide 24.6% of the redshifts, about two thirds of them being spectroscopic. SDSS-based catalogues yield 11.7% of the redshifts, of which more than half of which are spectroscopic. NED and SIMBAD database searches yield 5.9% of the redshifts, the vast majority of which are spectroscopic. PanSTARRS data provide 4.4% of the redshifts, all of which are photometric. Finally, association with the SPT and ACT SZ catalogues represent  $\sim 3.5\%$  of all redshifts, most of which are spectroscopic.

For the *Planck* clusters with measured redshifts, we have provided a homogeneously-defined mass estimated from the Compton  $Y$  parameter. The  $M-z$  distribution of the *Planck* clusters is shown by open red circles in Fig. 1, where it is compared with other large cluster surveys. Note that the masses are not homogenised and some clusters may appear several times due to differences in the mass estimation methods between surveys. We see that *Planck* cluster distribution probes a unique region in the  $M-z$  space occupied by massive,  $M \geq 5 \times 10^{14} M_\odot$ , high-redshift ( $z \geq 0.5$ ) clusters. The *Planck* detections almost double the number of massive clusters above redshift 0.5 with respect to other surveys.

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Table 1: Summary of the updates of PSZ1v2 for each cluster or candidate type

	PSZ1 (2013)			UPDATES	PSZ1v2 (2015)		
	Number	redshift			Number	redshift	
		type	number			type	number
<i>“Previously known”</i>	<b>683</b>	undef	29	<b>0</b>	<b>683</b>	undef	21
		estim	5	−8		estim	1
		phot	97	−43		phot	54
		spec	552	+55		spec	607
<i>“Planck discovered”</i>	<b>178</b>	undef	19	<b>+86</b>	<b>264</b>	undef	13
		phot	72	−6		phot	122
		spec	87	+50		spec	129
<i>Class − 1</i>	<b>54</b>	undef	54	<b>−30</b>	<b>24</b>	undef	24
		phot		−30		phot	
		spec		+22		spec	
<i>Class − 2</i>	<b>170</b>	undef	170	<b>−40</b>	<b>130</b>	undef	130
		phot		−40		phot	
		spec		+26		spec	
<i>Class − 3</i>	<b>142</b>	undef	142	<b>−16</b>	<b>126</b>	undef	126
		phot		−16		phot	
		spec		+10		spec	
		spec		+6		spec	

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## Appendix A: Description of the updated PSZ1 catalogue

The updated *Planck* catalogue of SZ sources is available at PLA<sup>5</sup> and SZ cluster database<sup>6</sup>.

The updated PSZ1 gathers in a single Table all the entries of the delivered catalogue based mainly on the *Planck* data and

<sup>5</sup> [http://www.sciops.esa.int/index.php?page=Planck\\_Legacy\\_Archive&project=planck](http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck)

<sup>6</sup> <http://szcluster-db.ias.u-psud.fr>

of the external validation information, based on ancillary data (Appendices B and C of *Planck Collaboration XXIX (2013)* respectively). It also contains additional entries. It is provided in a fits format, together with a readme file.

The updated catalogue contains, when available, cluster external identifications<sup>7</sup> and consolidated redshifts. We added two new entries namely the redshift type and the bibliographic reference. The three entries associated with the consolidated redshift reported in the catalogue are thus:

- Type of redshift: a string providing the different cases.
  - undef: undefined
  - estim: estimated from galaxies magnitudes
  - phot: photometric redshift
  - spec: spectroscopic redshifts
- Source for redshift: an integer value representing the origin of the redshifts.
  - 1: No redshift available
  - 1: MCXC updated compilation
  - 2: Databases NED and SIMBAD-CDS
  - 3: SDSS cluster catalogue from [Wen et al. \(2012\)](#)
  - 4: SDSS cluster catalogue from [Szabo et al. \(2011\)](#)
  - 5: SPT
  - 6: ACT
  - 7: Search in SDSS galaxy catalogue from *Planck* Collab. from Fromenteau PhD 2010 and Fromenteau et al. (private comm.)
  - 8: SDSS catalogue from [Rozo et al. \(2014\)](#)
  - 10: Pan-STARRS1 Survey confirmation
  - 20: XMM-Newton confirmation from *Planck* Collab.

<sup>7</sup> The external identification corresponds to the first identifier as defined in the external validation hierarchy adopted in *Planck Collaboration XXIX (2013)*.

- 50: ENO confirmation from *Planck* Collab.  
 60: WFI-imaging confirmation from *Planck* Collab.  
 65: NTT-spectroscopic confirmation from *Planck* Collab.  
 500: RTT confirmation from *Planck* Collab.  
 600: NOT confirmation from *Planck* Collab.  
 650: GEMINI-spectroscopic confirmation from *Planck* Collab.  
 – Bibliographical references for the redshift

We also added a new entry describing further the quality of the SZ detection. This is the flag  $Q_N$  derived from the artificial neural network SED-based quality assessment described in [Aghanim et al. \(2014\)](#).

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- <sup>1</sup> APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France  
<sup>2</sup> Aalto University Metsähovi Radio Observatory, Metsähovintie 114, FIN-02540 Kylmäla, Finland  
<sup>3</sup> Academy of Sciences of Tatarstan, Bauman Str., 20, Kazan, 420111, Republic of Tatarstan, Russia  
<sup>4</sup> African Institute for Mathematical Sciences, 6-8 Melrose Road, Muizenberg, Cape Town, South Africa  
<sup>5</sup> Agenzia Spaziale Italiana Science Data Center, Via del Politecnico snc, 00133, Roma, Italy  
<sup>6</sup> Agenzia Spaziale Italiana, Viale Liegi 26, Roma, Italy  
<sup>7</sup> Astrophysics Group, Cavendish Laboratory, University of Cambridge, J J Thomson Avenue, Cambridge CB3 0HE, U.K.  
<sup>8</sup> Astrophysics & Cosmology Research Unit, School of Mathematics, Statistics & Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa  
<sup>9</sup> Atacama Large Millimeter/submillimeter Array, ALMA Santiago Central Offices, Alonso de Cordova 3107, Vitacura, Casilla 763 0355, Santiago, Chile  
<sup>10</sup> CITA, University of Toronto, 60 St. George St., Toronto, ON M5S 3H8, Canada  
<sup>11</sup> CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France  
<sup>12</sup> California Institute of Technology, Pasadena, California, U.S.A.  
<sup>13</sup> Centre for Theoretical Cosmology, DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, U.K.  
<sup>14</sup> Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal  
<sup>15</sup> Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Plaza San Juan, 1, planta 2, E-44001, Teruel, Spain  
<sup>16</sup> Computational Cosmology Center, Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.  
<sup>17</sup> Consejo Superior de Investigaciones Científicas (CSIC), Madrid, Spain  
<sup>18</sup> DSM/Irfu/SPP, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France  
<sup>19</sup> DTU Space, National Space Institute, Technical University of Denmark, Elektrovej 327, DK-2800 Kgs. Lyngby, Denmark  
<sup>20</sup> Département de Physique Théorique, Université de Genève, 24, Quai E. Ansermet, 1211 Genève 4, Switzerland  
<sup>21</sup> Departamento de Física Fundamental, Facultad de Ciencias, Universidad de Salamanca, 37008 Salamanca, Spain  
<sup>22</sup> Departamento de Física, Universidad de Oviedo, Avda. Calvo Sotelo s/n, Oviedo, Spain  
<sup>23</sup> Department of Astronomy and Astrophysics, University of Toronto, 50 Saint George Street, Toronto, Ontario, Canada  
<sup>24</sup> Department of Astronomy and Geodesy, Kazan Federal University, Kremlevskaya Str., 18, Kazan, 420008, Russia  
<sup>25</sup> Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands  
<sup>26</sup> Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California, U.S.A.  
<sup>27</sup> Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia, Canada  
<sup>28</sup> Department of Physics and Astronomy, Dana and David Dornsife College of Letter, Arts and Sciences, University of Southern California, Los Angeles, CA 90089, U.S.A.  
<sup>29</sup> Department of Physics and Astronomy, University College London, London WC1E 6BT, U.K.  
<sup>30</sup> Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, U.K.  
<sup>31</sup> Department of Physics, Florida State University, Keen Physics Building, 77 Chieftan Way, Tallahassee, Florida, U.S.A.  
<sup>32</sup> Department of Physics, Gustaf Hällströmin katu 2a, University of Helsinki, Helsinki, Finland  
<sup>33</sup> Department of Physics, Princeton University, Princeton, New Jersey, U.S.A.  
<sup>34</sup> Department of Physics, University of California, Berkeley, California, U.S.A.  
<sup>35</sup> Department of Physics, University of California, One Shields Avenue, Davis, California, U.S.A.  
<sup>36</sup> Department of Physics, University of California, Santa Barbara, California, U.S.A.  
<sup>37</sup> Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois, U.S.A.  
<sup>38</sup> Dipartimento di Fisica e Astronomia G. Galilei, Università degli Studi di Padova, via Marzolo 8, 35131 Padova, Italy  
<sup>39</sup> Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44122 Ferrara, Italy  
<sup>40</sup> Dipartimento di Fisica, Università La Sapienza, P. le A. Moro 2, Roma, Italy  
<sup>41</sup> Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria, 16, Milano, Italy  
<sup>42</sup> Dipartimento di Fisica, Università degli Studi di Trieste, via A. Valerio 2, Trieste, Italy  
<sup>43</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Via della Ricerca Scientifica, 1, Roma, Italy  
<sup>44</sup> Discovery Center, Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark  
<sup>45</sup> Dpto. Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain  
<sup>46</sup> European Southern Observatory, ESO Vitacura, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago, Chile  
<sup>47</sup> European Space Agency, ESAC, Planck Science Office, Camino bajo del Castillo, s/n, Urbanización Villafranca del Castillo, Villanueva de la Cañada, Madrid, Spain  
<sup>48</sup> European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands  
<sup>49</sup> Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FIN-21500, Piikkiö, Finland  
<sup>50</sup> GEPI, Observatoire de Paris, Section de Meudon, 5 Place J. Janssen, 92195 Meudon Cedex, France  
<sup>51</sup> Helsinki Institute of Physics, Gustaf Hällströmin katu 2, University of Helsinki, Helsinki, Finland  
<sup>52</sup> INAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, Catania, Italy  
<sup>53</sup> INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, Padova, Italy  
<sup>54</sup> INAF - Osservatorio Astronomico di Roma, via di Frascati 33, Monte Porzio Catone, Italy  
<sup>55</sup> INAF - Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, Trieste, Italy  
<sup>56</sup> INAF Istituto di Radioastronomia, Via P. Gobetti 101, 40129 Bologna, Italy  
<sup>57</sup> INAF/IASF Bologna, Via Gobetti 101, Bologna, Italy  
<sup>58</sup> INAF/IASF Milano, Via E. Bassini 15, Milano, Italy  
<sup>59</sup> INFN, Sezione di Bologna, Via Imerio 46, I-40126, Bologna, Italy  
<sup>60</sup> INFN, Sezione di Roma 1, Università di Roma Sapienza, Piazzale Aldo Moro 2, 00185, Roma, Italy

- <sup>61</sup> IPAG: Institut de Planétologie et d’Astrophysique de Grenoble, Université Joseph Fourier, Grenoble 1 / CNRS-INSU, UMR 5274, Grenoble, F-38041, France
- <sup>62</sup> ISDC Data Centre for Astrophysics, University of Geneva, ch. d’Ecogia 16, Versoix, Switzerland
- <sup>63</sup> IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411 007, India
- <sup>64</sup> Imperial College London, Astrophysics group, Blackett Laboratory, Prince Consort Road, London, SW7 2AZ, U.K.
- <sup>65</sup> Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, U.S.A.
- <sup>66</sup> Institut Néel, CNRS, Université Joseph Fourier Grenoble I, 25 rue des Martyrs, Grenoble, France
- <sup>67</sup> Institut Universitaire de France, 103, bd Saint-Michel, 75005, Paris, France
- <sup>68</sup> Institut d’Astrophysique Spatiale, CNRS (UMR8617) Université Paris-Sud 11, Bâtiment 121, Orsay, France
- <sup>69</sup> Institut d’Astrophysique de Paris, CNRS (UMR7095), 98 bis Boulevard Arago, F-75014, Paris, France
- <sup>70</sup> Institute for Space Sciences, Bucharest-Magurale, Romania
- <sup>71</sup> Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan
- <sup>72</sup> Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, U.K.
- <sup>73</sup> Institute of Theoretical Astrophysics, University of Oslo, Blindern, Oslo, Norway
- <sup>74</sup> Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, La Laguna, Tenerife, Spain
- <sup>75</sup> Instituto de Física de Cantabria (CSIC-Universidad de Cantabria), Avda. de los Castros s/n, Santander, Spain
- <sup>76</sup> Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, U.S.A.
- <sup>77</sup> Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, U.K.
- <sup>78</sup> Kavli Institute for Cosmology Cambridge, Madingley Road, Cambridge, CB3 0HA, U.K.
- <sup>79</sup> LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
- <sup>80</sup> LERMA, CNRS, Observatoire de Paris, 61 Avenue de l’Observatoire, Paris, France
- <sup>81</sup> Laboratoire AIM, IRFU/Service d’Astrophysique - CEA/DSM - CNRS - Université Paris Diderot, Bât. 709, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France
- <sup>82</sup> Laboratoire Traitement et Communication de l’Information, CNRS (UMR 5141) and Télécom ParisTech, 46 rue Barrault F-75634 Paris Cedex 13, France
- <sup>83</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier Grenoble I, CNRS/IN2P3, Institut National Polytechnique de Grenoble, 53 rue des Martyrs, 38026 Grenoble cedex, France
- <sup>84</sup> Laboratoire de Physique Théorique, Université Paris-Sud 11 & CNRS, Bâtiment 210, 91405 Orsay, France
- <sup>85</sup> Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.
- <sup>86</sup> MPA Partner Group, Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Nandan Road 80, Shanghai 200030, China
- <sup>87</sup> Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
- <sup>88</sup> Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany
- <sup>89</sup> McGill Physics, Ernest Rutherford Physics Building, McGill University, 3600 rue University, Montréal, QC, H3A 2T8, Canada
- <sup>90</sup> MilliLab, VTT Technical Research Centre of Finland, Tietotie 3, Espoo, Finland
- <sup>91</sup> Moscow Institute of Physics and Technology, Dolgoprudny, Institutsky per., 9, 141700, Russia
- <sup>92</sup> National University of Ireland, Department of Experimental Physics, Maynooth, Co. Kildare, Ireland
- <sup>93</sup> Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark
- <sup>94</sup> Observational Cosmology, Mail Stop 367-17, California Institute of Technology, Pasadena, CA, 91125, U.S.A.
- <sup>95</sup> Optical Science Laboratory, University College London, Gower Street, London, U.K.
- <sup>96</sup> SB-ITP-LPPC, EPFL, CH-1015, Lausanne, Switzerland
- <sup>97</sup> SISSA, Astrophysics Sector, via Bonomea 265, 34136, Trieste, Italy
- <sup>98</sup> SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, U.K.
- <sup>99</sup> School of Physics and Astronomy, Cardiff University, Queens Buildings, The Parade, Cardiff, CF24 3AA, U.K.
- <sup>100</sup> Space Research Institute (IKI), Russian Academy of Sciences, Profsoyuznaya Str, 84/32, Moscow, 117997, Russia
- <sup>101</sup> Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.
- <sup>102</sup> Special Astrophysical Observatory, Russian Academy of Sciences, Nizhniy Arkhyz, Zelenchukskiy region, Karachai-Cherkessian Republic, 369167, Russia
- <sup>103</sup> Stanford University, Dept of Physics, Varian Physics Bldg, 382 Via Pueblo Mall, Stanford, California, U.S.A.
- <sup>104</sup> Sub-Department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, U.K.
- <sup>105</sup> TÜBİTAK National Observatory, Akdeniz University Campus, 07058, Antalya, Turkey
- <sup>106</sup> Theory Division, PH-TH, CERN, CH-1211, Geneva 23, Switzerland
- <sup>107</sup> UPMC Univ Paris 06, UMR7095, 98 bis Boulevard Arago, F-75014, Paris, France
- <sup>108</sup> Universität Heidelberg, Institut für Theoretische Astrophysik, Philosophenweg 12, 69120 Heidelberg, Germany
- <sup>109</sup> Université Denis Diderot (Paris 7), 75205 Paris Cedex 13, France
- <sup>110</sup> Université de Toulouse, UPS-OMP, IRAP, F-31028 Toulouse cedex 4, France
- <sup>111</sup> Universities Space Research Association, Stratospheric Observatory for Infrared Astronomy, MS 232-11, Moffett Field, CA 94035, U.S.A.
- <sup>112</sup> University Observatory, Ludwig Maximilian University of Munich, Scheinerstrasse 1, 81679 Munich, Germany
- <sup>113</sup> University of Granada, Departamento de Física Teórica y del Cosmos, Facultad de Ciencias, Granada, Spain
- <sup>114</sup> Warsaw University Observatory, Aleje Ujazdowskie 4, 00-478 Warszawa, Poland